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New process design for the gasification of waste using Fresnel solar collectors

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Sustainable Waste Management is crucial for reducing environmental impact of human activity. Various technologies have been devised to transform biomass and other waste into environmentally friendly energy sources, encompassing fuel, heat, electricity and organic fertilizer. The supercritical water gasification (SCWG) process could be a viable alternative to conventional treatments, since a high-quality gas is obtained as product. To minimize the cost-effectiveness of SCWG, in this work we propose the use of solar thermal energy supplied by Fresnell solar collectors specifically designed for high-pressure fluids and stored in an innovative heat-storing system. The design consists of a serpentine formed by a high-pressure piping. In order to transfer energy from the internal wall of the steel tube, hit by solar radiation, it is necessary to insert, between the spaces surrounding the individual high-pressure tubes, a highly conductive material, identified in a compact matrix of molten aluminum. This new process has been called SUNGAS and aims to significantly reduce operational costs by the exploitation of two different renewable sources, such as solar thermal energy and solid waste, thus promoting the application of this technology on an industrial scale. In the present paper, the design of the innovative continuous solar reactor at industrial scale is presented, together with thermal and empirical modeling based on the biomass conversion. Results show that SUNGAS could represent a feasible method for syngas production from OM and similar biomass waste.

* 1. Introduction

Waste management, including both industrial and urban waste, has become an environmental challenge due to a production chain still far from a circular economy model. The rapid human population growth decades have led to a significant increase in overall waste volume and in a rise in industrial production. According to the World Bank report, global waste generation is projected to reach 2,200 million tons per year by 2025, with energy demand expected to increase sixfold if current trends persist (Waqas et al. 2023).

Olive mills wastewater (OMW) and Organic Fraction of Municipal Solid Waste (OFMSW) are two types of wastes, produced in very large quantitative and rich in carbohydrates, lignin, proteins, lipids, and organic acids. Their organic content holds significant potential for valorization within a circular economy framework. In particular, the olive mills are a major source of environmental pollution in olive oil-producing countries, as are several Mediterranean sites. The extraction process requires significant water consumption and generates large volumes of waste streams within a short period. Olive oil production results in two main by-products: liquid waste known as olive mill wastewater (OMW), and a solid residue. OMW is highly polluted, with chemical oxygen demand (COD) levels reaching up to 300 g/L and has low biodegradability due to its acidity and strong toxicity, which negatively affect microorganisms, soil, plants, and animals. It is estimated that for every 1000 kg of olive processed, approximately 980 kg of waste is generated, consisting of 40% olive pomace and 60% liquid olive mill wastewater. This effluent contains about 80–90% water, depending on the extraction process used. (Lima et al. 2024; Al Manama et al. 2025).

It is crucial to recognize that many waste materials retain residual value, which, if properly harnessed, can transform an environmental encumbrance into an economic opportunity. In this context, sustainable waste management plays a key role in generating economic value through waste-to-energy conversion, material recovery, the extraction of valuable compounds, and advanced recycling strategies. Unlike other energy sources such as fossil fuels, photovoltaic, wind, hydropower, and geothermal energy—which require additional chemical processing—biomass can be directly converted into fuel (Quereshi et al. 2021). The global interest in biofuel production has been increasing due to the depletion of fossil fuel reserves and the urgent need to address climate change. Biofuels are considered a more sustainable alternative, contributing to both climate change mitigation and energy security (Musharavati et al. 2024; Rabbi et al. 2022). The production and utilization of biofuels such as biodiesel and bioethanol can significantly reduce the environmental impact associated with non-renewable fuel consumption (Gunarathne and Lee 2019) while alleviating pressure on conventional fuel resources (Hassan et al. 2022). Therefore, biomass conversion into biofuels plays a crucial role in expanding renewable energy sources, combating climate change, and reducing environmental degradation (Musharavati et al. 2024).

The supercritical water gasification (SCWG) process converts organic compounds into gaseous products within an aqueous system under conditions exceeding the critical point of water (374 °C and 22.1 MPa) (Correa et al. 2018). Beyond this threshold, water exhibits reduced density and viscosity, leading to enhanced diffusivity and minimized transport limitations. The system's dielectric constant is significantly reduced compared to subcritical water, transforming it into a universal solvent for organic compounds, polymers, and gases. Additionally, the elevated temperatures accelerate reaction kinetics, promoting the breakdown and the dissolution of complex organic compounds into lighter gases, at the same time the recombination of the intermediates into complex tars and chars is reduced (Heeley et al. 2024). As a result, gas mainly constituted by H2, CO, CO2, N2 is obtained in the gasification process, with a small quantitative of low molecular-weight hydrocarbons (CH4, C2H4, C2H6) and very small quantitative of H2S, NH3 and no production of NOx and SOx. Several studies in literature have explored the application of the SCWG process for various purposes. Examples include the production of hydrogen-rich gas mixtures from bread waste (Sathish et al. 2024), syngas production from motor oil (Maniscalco et al. 2021), the treatment of aqueous fractions containing high oil content (Xu et al. 2019), and the processing of lignocellulosic biomass. Additionally, SCWG has been investigated for the disposal of organic substances in autothermal systems, such as the treatment of wastewater from pig farming (Qi et al. 2024) and the processing of algal biomass (Caputo et al. 2016). All these results suggest that the OFMSW could be a suitable feedstock for gasification. In this context, waste-to-syngas processes promote sustainability by minimizing environmental impact and providing substantial economic returns.

To improve the economic feasibility of SCWG, various heat sources can be integrated, with renewable energy being a particularly promising option. Among these, solar thermal energy stands out as the most suitable alternative. In this study, the heat required to drive the SCWG process is supplied by modified Fresnel solar thermal collectors, specifically adapted for high-pressure fluids, and stored in an advanced thermal energy storage system. By harnessing both solar thermal energy and solid waste as renewable resources, this approach significantly lowers operational costs and enhances the scalability of SCWG for industrial applications.

In this paper a novel process, named Sungas, to valorize the residual organic matter by supercritical water gasification is proposed, where the required heat for the gasification is provided by a solar thermal system.

* 1. Process description

In Figure 1a simplified diagram of the proposed process is presented. Solar energy, used to supply heat to the gasification reactor, is concentrated by Fresnel collectors. The Linear Fresnel Collector is a system designed to heat a fluid using solar radiation. It consists of a series of linear heliostats, arranged horizontally near ground level, which reflect and concentrate solar rays onto a thermally insulated receiver tube located approximately ten meters above the ground. The heliostats are capable of rotating along their longitudinal axis to track the sun’s movement and continuously focus the reflected radiation on the receiver tube. The system primarily comprises the primary and secondary reflectors and the receiver tube. The primary reflector is the array of reflective strips forming the main reflective surface of the Fresnel collector. The secondary reflector, on the contrary, is the auxiliary component positioned above the receiver tube to redirect scattered radiation onto the tube, enhancing optical efficiency.



Figure 1. Scheme of the proposed process.

In the case studied in this work, the collector consists of six mirror subsystems, each approximately 12 meters wide and 6 meters long. Each collector, composed of 17 mirrors, each about 0.6 meters wide, has a total length of 38 meters and a width of 12 meters. The array of the reflector concentrates solar radiation onto the receiver system, at an elevated position, at a height of approximately 6 to 7 meters above ground level. The receiver consists of a high-efficiency thermal conduit through which the wastewater circulates. The design views a serpentine formed by a high-pressure Inconel 625 piping. This tube presents an external diameter of 6 mm, an internal diameter of 3 mm and the bundle is housed inside a steel tube of the solar receiver. To facilitate the transfer of energy from the inner wall of the steel tube, which is exposed to solar radiation, a highly conductive material is required in the spaces surrounding the individual high-pressure tubes. Within the tube bundle, water flows under supercritical conditions along a coil comprising 37 loops, each measuring 4 meters in length, resulting in a total length of 148 meters. As the fluid meets the tube’s surface, which is heated by concentrated solar radiation, its temperature increases. The component through which the heat transfer fluid flows is made of a specialized titanium-stabilized steel, measuring 4 meters in length and 70 mm in diameter. It is coated with multiple layers of highly absorbent materials and encased in a vacuum-sealed borosilicate glass tube with an anti-reflective treatment. At both ends of the tube, two linear compensators are placed to accommodate differential thermal expansions between the glass and steel and ensure the optimal performance of the receiver tube within the solar collector.

The operative temperature was fixed to about 400°C that represents a good compromise between construction requirements and sufficient gas yields. Immediately downstream of the supercritical reactor, the product gas enters in a series of filters, which remove char particles and ash. The recovered solids ca be collected for safe disposal or potential reuse as biochar. The remaining mixture of water and syngas then passes through a shell-and-tube heat exchanger. Here, sensible heat is transferred to a solid-state thermal energy storage (TES) unit which absorbs the residual thermal energy. After heat recovery, the stream is throttled through a first flash separator operating at high pressure, flashing off vapor and syngas while the remaining liquid is routed through an intermediate cooler. A second flash stage at lower pressure, then liberates any residual gases. This two-step flashing maximizes gas yield and allows staged removal of lighter and heavier components.

In industrial applications the produced syngas can be fed directly into downstream industrial furnaces, boilers, or gas engines, partially replacing natural gas or fuel oil. Alternatively, the syngas can be sent to an amine scrubber or membrane separator to selectively remove CO₂. After the H₂ enrichment, the purified stream becomes a high-quality combustion gas, with hydrogen concentrations typically in the 70–80 vol.% range. However, in the current configuration, no CO₂ scrubbing is applied, as the study is focused primarily on the upstream processes and the associated energy requirements. Methanation is another potential treatment for the gas, commonly applied to high-temperature gasification products. In this process, methane is synthesized through the catalytic recombination of hydrogen with carbon monoxide or carbon dioxide.

* 1. Materials and methods

A lab-scale system was used to gasify real olive mill effluent mimicking the real operative conditions, but in this case the heat was provided by electric resistances at the external reactor surface. The real olive mill effluent, provided by a Sicilian oil producer, had a total organic carbon (TOC) of about 6100 mg/L. An Inconel- cylindric reactor with a volume of 200 mL was the core of the process, while a pump has been employed to continuously feed the olive mill effluent with different flow rates.

Although the reaction is carried out in the absence of oxygen, carbon dioxide is formed. This occurs because water under supercritical conditions dissociates into H+ and OH− ions, which then react with the organic compounds present in the wastewater, following the possible mechanism (Kipçak, Söǧüt, and Akgün 2011):

$C\_{n}H\_{m}+nH\_{2}O\leftrightarrow nCO+ \left(\frac{m}{2}+n\right)H\_{2}$ (1)

$C+ H\_{2}O \leftrightarrow CO+H\_{2}$ (2)

$CO+ H\_{2}O \leftrightarrow CO\_{2}+ H\_{2}$ (3)

$CO+3H\_{2 }\leftrightarrow CH\_{4} \left(or C\_{2}H\_{4}, C\_{2}H\_{6}\right)+ H\_{2}O$ (4)

After the reaction, the effluent was then cooled and thanks to a separator, the gas was separated from the liquid phase and then analyzed by gas chromatography (Agilent 7890B).

* 1. Results and discussion

In order to have a mathematical model able to return the effective energy received by the reactor, a macroscopic energy balance was set. Referring to Figure 2, the total energy arriving to the reactor is given by Eq.(1):

$E\_{tot}= E\_{sun}^{I}+ E\_{sun}^{II}- E\_{refl}- E\_{boltz}- E\_{glass}$ (5)

Where $E\_{sun}^{I}$ and $E\_{sun}^{II}$ are the energy comes from the primary and secondary optical lens; $E\_{refl}$ is the energy reflected by the reactor external surface; $E\_{boltz}$ is the energy irradiate by the receiver at a certain temperature; $E\_{glass}$ is the energy absorbed and irradiated by the glass jacked placed around the receiver. This approach allows to regulate the energy given by the primary and secondary optical lens, in order to set the operative temperature.



Figure 2. Macroscopic energy balance on the receiver.

Using the temperature range achievable with the Fresnel lens, several tests were carried out in the laboratory setup.

An empirical model was then proposed to describe the conversion as a function of time and temperature, based on an exponential fitting approach, Eq. (2):

$Conversion=A\left(t\right) ∙ e^{B\left(t\right)T}$ (6)

Where t is the reaction time and T is the working temperature. A and B were fitting parameters, experimentally found in a laboratory setup, by varying the temperature and fixing the reaction time. Several tests were carried out in a temperature range between 400°C and 600°C with different reaction times. Conversion values between 20% and 90% were found and the results at different reaction times were summarized in the Figure 3.



Figure 3. Conversion values at different reaction times, varying the working temperature.

From the trend of each curve, an exponential law for the conversion can be extrapolated, expressed as a function of different A and B parameters. The equations reported in Table 1 were derived to define A and B for each residence time:

Table 1. Exponential equation describing the conversion-temperature trend, used to find the A and B values.

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| *Conversion (30 sec) = 0.0017 ∙ e0.0106T* |
| *Conversion (60 sec) = 0.0122 ∙ e0.0073T* |
| *Conversion (90 sec) = 0.0261 ∙ e0.0061T* |
| *Conversion (120 sec) = 0.0333 ∙ e0.0058T* |
| *Conversion (150 sec) = 0.2005 ∙ e0.0026T* |

A and B are the coefficients in the equations in Table 1 and are themselves functions of time. Their time dependence, reported in Eq. (3) and Eq. (4), were found by plotting their values at different resident times:

$A\left(t\right)= 2∙10^{-7}t^{2.6}$ (7)

$B\left(t\right)= -6∙10^{-5}t+0.01$ (8)

This simple empirical model represents a first approach to quickly obtaining a design of the reactor and its operative conditions.

The syngas was then analyzed and presented hydrogen concentration ranging between 12 and 38% with H2/CO ratio between 2.5 and 7. Its industrial application is closely linked to the gas quality; therefore, a thorough assessment of the potential applications of the produced gas, which necessitates a deeper analysis of its quality and composition, is planned as a subsequent phase of this research.

* 1. Conclusions

The present work proposed a novel process to valorize biomass from human activities, such as food wastes and olive mill effluents, that usually contains a huge amount of water. In fact, the high content of water could represent a problem for the treatment of this kind of organic mass forcing to a preliminary drying step, often very expensive. The SCWG, on the contrary, is able to treat directly this kind of wastes, with the possibility to obtain a good-quality syngas as product. A mathematical model was developed to describe the conversion behaviour, based on experimental data collected from laboratory tests that simulated real operating conditions. The proposed empirical model, although simple, provides valuable insights for the design of the full-scale reactor.

Futures development will focus on refining the mathematical model by incorporating detailed kinetic mechanisms and validating it against a broader experimental dataset. Additionally, further studies will explore the economic benefits of the proposed waste-to-syngas process.

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